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Optical transmission gratings by one driven three-level atom and a microtoroidal resonator

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ABSTRACT

Based on the strong coherent interaction between a three-level ladder-type atom and a fiber-taper-coupled microtoroidal resonator, we present a scheme for optical transmission gratings. Using experimentally accessible parameters, it is shown that alternating regions of high transmission and absorption can be created in the fiber-taper channel by spatially modulating an external coupling field. The model shows an obvious effect which has a direct analogy with the phenomenon of electromagnetically induced grating (EIG) in quantum systems.

1. Introduction

Electromagnetically induced grating (EIG) [1], which is attributed to destructive quantum interference, is an interesting phenomenon where the absorption of a weak probe beam coupled to an atomic transition can be spatially modulated (reduced absorption at the peaks of the standing-wave field and high absorption at the nodes) by applying a strong standing wave that is coupled to another atomic transition in a three-level atomic system. EIG was originally observed in cold three-level atomic vapors [2]. Afterward, it was demonstrated that such an EIG effect can be used to store probe pulses in a vapor of rubidium atoms [3], to achieve tunable photonic band gap [4], to devise a dynamic controlled cavity [5], to implement optical routing [6,7], and so on. However, as shown in [1], low efficiency of the EIG due to weak interactions between single atoms and photons in a three-level atomic medium restricts its practical uses.

It is worth pointing out that, on account of both highly confined microscale mode volume and ultrahigh quality factors [8–10], optical microresonators enable strong light-matter interactions as well as drastic reductions of the power necessary to observe strong nonlinear effects [11–14]. As a result, in the past few years optical microresonators are increasingly gaining interest in many diverse areas of research, ranging from nanophotonics [15,16] and biochemical sensing [17–19] to cavity quantum electrodynamics (CQED) [20,21]. Optical microresonators support whispering-gallery modes (WGMs). Different from the standing modes in a conventional Fabry–Perot (F–P) cavity, WGMs are a type of traveling modes. In other words, WGM microresonators typically support two counterpropagating modes, i.e., clockwise (CW) and counterclockwise (CCW) propagating modes, with the same polarization and a degenerate frequency. This degeneracy can be lifted, and it can form a doublet through backscattering coupling induced by internal defect centers or surface roughness [22,23]. This phenomenon is known as modal coupling. Atoms in the vicinity of the resonator are able to interact with the two WGMs via the evanescent field. With the help of the fiber taper, the efficiency for coupling the quantum fields into and out of the microtoroidal resonator can approach 0.99–0.999 [24,25]. Also, strong coupling between a single cesium atom and the electromagnetic mode in a microtoroid has been theoretically investigated and experimentally observed [26]. Under a certain condition, the atom can transfer its excitation to the CW or CCW mode which is intrinsic in the microtoroidal resonators.

In view of this, making use of the above-mentioned coherent interactions between the microtoroidal resonator and atoms, some schemes about photon turnstiles [27], photon routers [28], single-photon transistors [29] and quantum controlled-phase-flip gates [30,31] have been put forward. It is worth pointing out that, in the investigation of Ref. [27], Dayan et al. have addressed that, with quantum critical coupling of input lights into and out of a microtoroidal resonator, a single cesium atom near the surface of the resonator can dynamically control the cavity output depending on the photon number at the input. Based on these achieved advances, we demonstrate that such a system can be employed to act as a kind of optical transmission gratings, analogous to an EIG in a three-level atomic system [1]. Using experimentally accessible parameters, alternating regions of high transmission and absorption can be caused by an external standing-wave coupling field.

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Due to its robustness against major experimental imperfections together with the high efficiency for coupling of the quantum fields into and out of the resonator with a fiber taper [24,25], this work might broaden variety applications in imaging techniques and precise measurements compared with EIG in a three-level atomic system [1]. On the other hand, in contrast to traditional F–P cavities, microtoroidal resonator structures possess advantages in easy integration and fabrication. They will likely be valuable for potential device applications.

The remainder of this paper is arranged into three parts as follows. In Section 2, we establish the physical model and its theoretical description. By solving the coupled amplitude equations of motion for the microtoroidal resonator, the tapered fiber and the three-level ladder-type atom in the frequency domain, we derive explicit analytical expressions of the forward- and backward-propagating transmission functions for the output fields. In Section 3, we devote to analyzing and demonstrating in details optical transmission gratings in this device. At the same time, we also present the principal mechanism behind the transmission grating. Finally, our main conclusions are summarized in Section 4.

2. Model and equations

Fig. 1 is a schematic description of the composite system, which consists of a microtoroidal resonator, a tapered fiber, and a three-level ladder-type atom. A microtoroidal resonator has two internal counter-propagating modes which are described in terms of the annihilation operators $\hat{a}$ and $\hat{b}$ with a common frequency ω_c in the absence of scattering [27]. These two modes are coupled to each other in the presence of scattering with a strength that is parameterized by h. The intracavity field decays at a rate $\kappa=\kappa_i+\kappa_{ex}$, where κ_i and κ_{ex} describe intrinsic losses and extrinsic loss due to adjustable interaction with the modes of a tapered fiber. The intracavity fields are coupled to a tapered fiber with high efficiency $\eta>0.99$ [24,25]. The evanescent fields of modes $\hat{a}$ and $\hat{b}$ have the coherent interactions with a ground state $|g\rangle$ and an upper excited state $|r\rangle$ with the energy ω_r of a three-level ladder-type atom near the external surface of the microtoroidal resonator. It is convenient to describe the interaction by the normal modes of the microtoroidal resonator $\hat{A}=\frac{1}{\sqrt{2}}\left(\hat{a}+\hat{b}\right)$ and $\hat{B}=\frac{1}{\sqrt{2}}\left(\hat{a}-\hat{b}\right)$ with the coupling rates g_A and g_B, respectively, where $g_{A,B}\sim g_0 e^{-\delta\rho}\{\cos kz, \sin kz\}$ $(\delta\sim\frac{1}{\lambda})$ with ρ being the radial distance from the surface of the toroid to the atom, z being the position around the circumference of the resonator, and k being the vacuum wave vector. As a result, depending on the position of the three-level ladder-type atom, coupling may occur predominantly (or even exclusively) to only one of the two normal modes [26,27]. Hereafter, we assume the position of the atom such that $kz=n\pi$ (n is integer), i.e., $g_B=0$, then the normal mode $\hat{B}$ is decoupled from the interaction with the atom. Alternatively, the upmost state $|e\rangle$ of the three-level ladder-type atom (with the energy ω_e) is coupled to the state $|r\rangle$ by a classical standing-wave coupling field with central frequency ω_{sw} and position-dependent Rabi frequency $\Omega_{sw}(x)$. The interactions between a high-Q microresonators (or microcavities) and a three-level system have been intensively studied previously [29,32–36] but in different contexts.

Following the method developed in Refs. [26,27], the total Hamiltonian describing the interaction of a microtoroidal resonator with a three-level ladder-type atom and with a tapered fiber (see Fig. 1) can be written in the form

$$\begin{aligned}\hat{\mathcal{H}}/\hbar =\ & \omega_r|r\rangle\langle r| + \omega_e|e\rangle\langle e| + (\omega_c+h)\hat{A}^\dagger\hat{A} \\ & + \int_{-\infty}^{+\infty}\omega\left(\hat{a}_{1\omega}^\dagger\hat{a}_{1\omega}+\hat{a}_{2\omega}^\dagger\hat{a}_{2\omega}\right)d\omega + g_A\left(i|r\rangle\langle g|\hat{A}-i|g\rangle\langle r|\hat{A}^\dagger\right) \\ & + \left[i\Omega_{sw}(x)e^{-i\omega_{sw}t}|e\rangle\langle r| - i\Omega_{sw}^*(x)e^{i\omega_{sw}t}|r\rangle\langle e|\right] \\ & + \int_{-\infty}^{+\infty}\sqrt{\frac{\kappa_{ex}}{2\pi}}\left(i\hat{a}_{1\omega}^\dagger\hat{A}-i\hat{A}^\dagger\hat{a}_{1\omega}\right)d\omega \\ & + \int_{-\infty}^{+\infty}\sqrt{\frac{\kappa_{ex}}{2\pi}}\left(i\hat{a}_{2\omega}^\dagger\hat{A}-i\hat{A}^\dagger\hat{a}_{2\omega}\right)d\omega,\end{aligned} \tag{1}$$

where the energy of state $|g\rangle$ has been set as zero. $\hbar\omega_r$ and $\hbar\omega_e$ are the energies of the atomic states $|r\rangle$ and $|e\rangle$, respectively. The symbols $|m\rangle\langle n|$ (m, $n=g$, e, r) for $m\neq n$, are the atomic transition or projection operators between the states $|m\rangle$ and $|n\rangle$ involving the levels of the atom while $|m\rangle\langle m|$ represent the atomic population operators [see also the bubble of Fig. 1]. $\hat{A}$ and $\hat{A}^\dagger$ are the bosonic annihilation and creation operators of the normal mode with the frequency ω_c+h, where ω_c is the "bare" cavity mode frequency. $\hat{a}_{j\omega}$ and $\hat{a}_{j\omega}^\dagger$ $(j=1,2)$ are the annihilation and creation operators for the two modes of frequency ω in the tapered fiber channel, with the commutation relations $\left[\hat{a}_{j\omega},\hat{a}_{j\omega'}^\dagger\right]=\delta(\omega-\omega')$. $\sqrt{\kappa_{ex}/2\pi}$ describes the coupling strength between the toroidal resonator mode and the tapered fiber mode.

According to the spirit of Refs. [37,38], we choose the proper free Hamiltonian to transform to the interaction picture, that is,

$$\hat{\mathcal{H}}_{int} = e^{i\hat{\mathcal{H}}_0 t/\hbar}\hat{\mathcal{H}}_{res}e^{-i\hat{\mathcal{H}}_0 t/\hbar}, \tag{2}$$

$$\hat{\mathcal{H}}_0/\hbar = (\omega_c+h)\hat{A}^\dagger\hat{A} + (\omega_c+h)|r\rangle\langle r| + (\omega_c+h+\omega_{sw})|e\rangle\langle e|$$

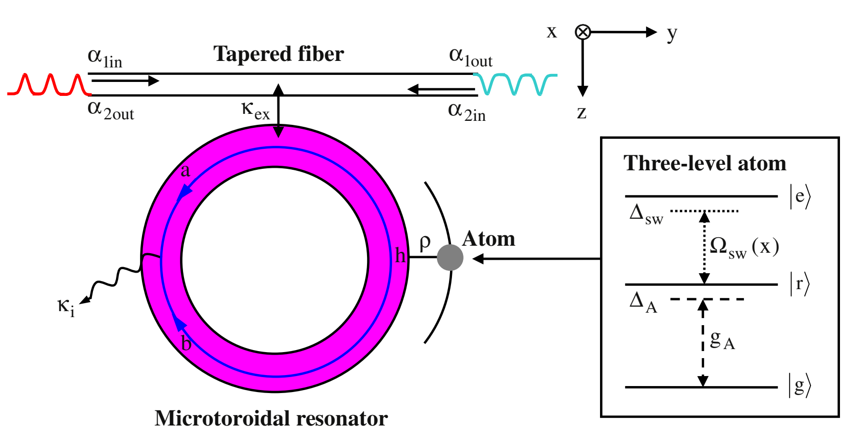

Fig. 1. A schematic of the microtoroidal resonator and fiber taper system. The tapered fiber and the resonator are in the critical coupling and the atom is located with well-defined azimuthal phase $kz=n\pi$ (n is integer) [18,27]. In this case, the atomic transition $|g\rangle\leftrightarrow|r\rangle$ is coupled to the normal mode $\hat{A}$ of the microtoroidal resonator with strength g_A and frequency ω_c+h (ω_c is the "bare" cavity mode frequency). At the same time, the $|r\rangle\leftrightarrow|e\rangle$ transition is driven by a classical standing-wave coupling field with position-dependent Rabi frequency $\Omega_{sw}(x)$ and central frequency ω_{sw}. The standing-wave coupling field is aligned along the x axis perpendicular to the y–z plane.